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SONYC - Substellar Objects in Nearby Young Clusters

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Abstract. The origin of the lowest mass free-floating objects – brown dwarfs and planetary-mass objects – is one of the major unsolved problems in star formation. Establishing a census of young substellar objects is a fundamental prerequisite for distinguishing between competing theoretical scenarios. Such a census allows us to probe the initial mass function (IMF), binary statistics, and properties of accretion disks. Our SONYC (Substellar Objects in Nearby Young Clusters) survey relies on extremely deep wide-field optical and near-infrared imaging, with follow-up spectroscopy, in combination with Spitzer photometry to probe the bottom end of the IMF to unprecedented levels. Here we present SONYC results for three different regions: NGC 1333, ρ Ophiuchus and Chamaeleon-I. In NGC 1333, we find evidence for a possible cutoff in the mass function at 10-20 Jupiter masses. In ρ Oph we report a new brown dwarf with a mass close to the deuterium-burning limit.

1. Introduction

The origin of the stellar initial mass function (IMF) is one of the major issues in astrophysics. The low-mass end of the IMF, in particular, has been subject of numerous observational and theoretical studies over the past decade (see Bonnell et al. 2007). Star forming regions and young clusters harbor a large population of free-floating objects below the stellar-mass boundary, found to be at ~0.075 $M_{\odot}$. These objects include brown dwarfs (BDs), but also a population of objects with masses comparable to those of massive planets (we refer to these objects as "planetary-mass objects" or PMOs). Despite the large advances in our understanding of substellar objects over the past decade, some of the most important questions still remain unanswered. The origin of BDs and PMOs is not clear (Whitworth & Goodwin 2005); competing scenarios include turbulent fragmentation (Padoan & Nordlund 2004), ejection from multiple systems (Bate 2009), and ejection from fragmenting protoplanetary disks (Stamatellos & Whitworth 2008). The shape of the IMF at very low masses is the subject of an ongoing debate in

the literature (Bonnell et al. 2007; Chabrier 2003). In nearby star forming regions the total number BDs relative to the number of low-mass stars varies between 3 and 8 with large uncertainties (Andersen et al. 2008). The number of PMOs and its dependence on environment is even more uncertain. The IMF could be still rising below $0.015 M_{\odot}$ (Caballero et al. 2007), or declining in this regime (Lucas et al. 2005). A cutoff in the mass function has not been observed yet.

SONYC – Substellar Objects in Nearby Young Clusters – is an ongoing project to provide a complete census of the brown dwarf and planetary mass object population in nearby young clusters, and to establish the frequency of substellar mass objects as a function of cluster environment. The resulting catalog of substellar mass candidates will provide the basis for detailed characterization of their physical properties (disks, binarity, atmospheres, accretion, activity). The primary means of identifying candidates is broad-band imaging in the optical and the infrared, thus aiming to detect the photosphere. The survey is also combined with the 2MASS and Spitzer photometry catalogs. Photometric selection results in large samples of candidates and requires extensive spectroscopic follow-up to asses the real nature of the objects. Our observations are designed to reach limiting masses of $\sim 0.005\,M_{\odot}$, well below the deuterium-burning limit at $0.015\,M_{\odot}$, and thus require us of 4- to 8-m-class telescopes. By probing several star forming regions we want to probe for environmental differences in the frequency and properties of substellar objects.

In this contribution, we summarize the results delivered in the framework of SONYC over the past two years. We have surveyed three star forming regions: NGC 1333 (Scholz et al. 2009), ρ Ophiuchus (Geers et al. 2010), and Chamaeleon-I (Mužić et al., submitted to ApJ).

2. NGC 1333

NGC 1333 is a cluster in the Perseus star forming complex, with an age of ∼1 Myr, a distance of ∼300 pc (de Zeeuw et al. 1999; Belikov et al. 2002), and moderate extinction. The spatial coverage of our survey in NGC 1333 is $0.25\,\mathrm{deg}^2$ (see Fig 1).

2.1. Photometry and Spectroscopy

Imaging of NGC 1333 was performed at the Subaru telescope. We used the Suprime-Cam wide-field optical imager (Miyazaki et al. 2002) to obtain images in SDSS filters i' and z', and MOIRCS (Suzuki et al. 2008; Ichikawa et al. 2006) for near-infrared J and K_S observations. Our data are complete down to i'=24.7, z'=23.8, J=20.8, and K_S=18.0 mag. In terms of object masses for members of NGC 1333, this roughly corresponds to mass limits of $0.008 M_{\odot}$ for $A_V \lesssim 10$ and $0.004 M_{\odot}$ for $A_V \lesssim 5$, based on the COND03 (Baraffe et al. 2003) and DUSTY00 (Chabrier et al. 2000) evolutionary tracks. We used MOIRCS again to carry out multi-object spectroscopy for 53 sources in NGC 1333, selected on the basis of their broad-band colors that are in the range as expected for substellar cluster members. This sample does not show any bias in spatial coverage or optical/NIR colors with respect to the full photometric candidate sample. The wavelength coverage for MOIRCS low-resolution spectroscopy includes H- and K-bands.

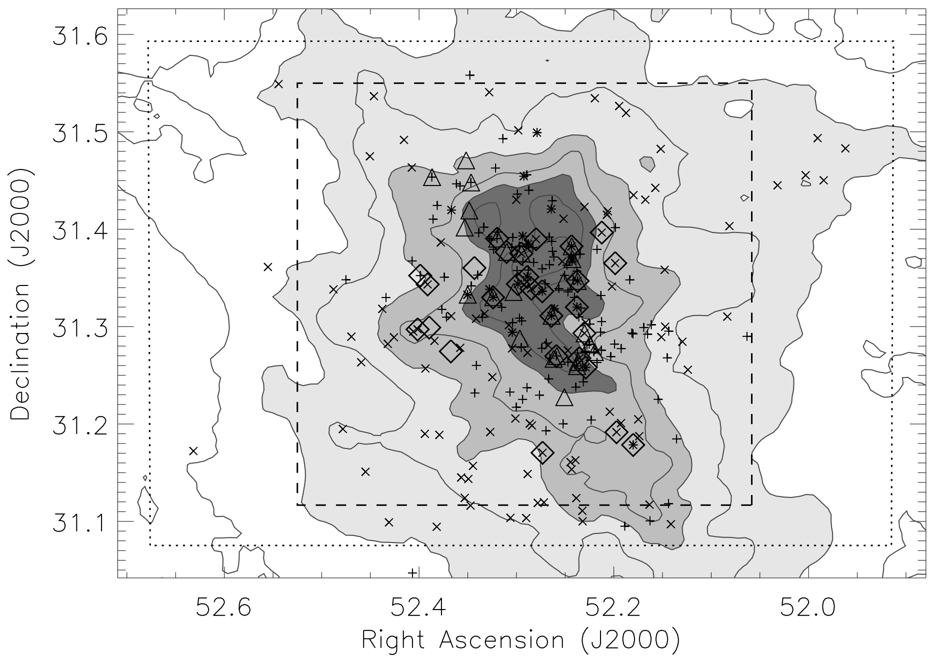

Figure 1. Spatial coverage of our survey in NGC 1333. Crosses are all candidates selected from optical photometry with $i' > 18.5$, diamonds the spectroscopically confirmed substellar members, triangles the confirmed BDs from Wilking et al. (2004). The plusses are YSO candidates from Spitzer data without spectroscopic confirmation from Gutermuth et al. (2008). The underlying contours show the distribution of ^{13}CO from the J=1 – 0 map by Ridge et al. (2006). The dotted and dashed lines show the area covered in our optical and NIR survey, respectively. Image from Scholz et al. (2009); reproduced by permission of the AAS.

2.2. Results

Our goal is to identify young sources with effective temperatures at or below 3000 K. As outlined in detail in Scholz et al. (2009), these objects show a characteristic spectral shape in the near-infrared. In particular, their spectra have a clear peak in the H-band (Cushing et al. 2005). This feature is caused by water absorption on both sides of the H-band. The depth of this feature depends strongly on effective temperature. While the H-band peak appears round in old field dwarfs, it is triangular in young, low-gravity sources. In addition, young brown dwarfs are expected to have flat or increasing K_S-band spectra with CO absorption bands at $\lambda > 2.3\,\mu$m. To estimate the effective temperatures of the BD candidates we perform fitting of model spectra from the DUSTY series (Allard et al. 2001) to our observed spectra. We confirm 19 sources with effective temperatures of 3000 K or lower. Combined with the clear indications for youth, we classify them as probable substellar members of NGC 1333.

Combining our survey results with previous studies, the current census of spectroscopically confirmed BDs in NGC 1333 is 33. The ratio of substellar to stellar members with masses below $1 M_\odot$ is 1.5 ± 0.3, lower by a factor of 2 – 5 than in all other previously surveyed regions. Thus, NGC 1333 clearly shows an overabundance of BDs. On the other hand, the cluster shows lack of PMOs. The low-mass limit of the confirmed

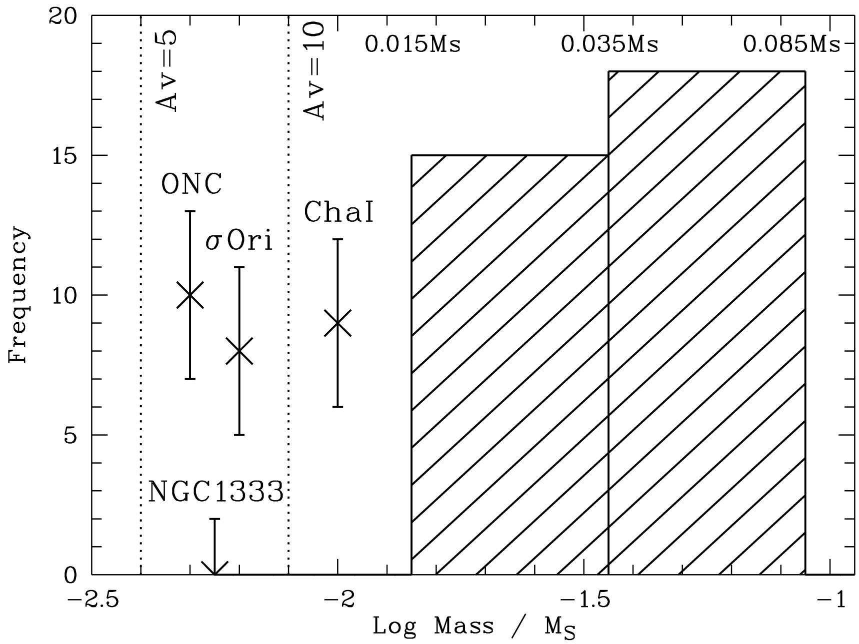

Figure 2. Mass distribution of BDs in NGC 1333 (hatched histogram) and the deficit of planetary-mass objects. The three labeled data points show the predicted number of PMOs in NGC 1333 based on the surveys in σ Ori, the ONC, and in Cha-I. The error bars correspond to 1σ. Image from Scholz et al. (2009); reproduced by permission of the AAS.

BDs is 0.012 – 0.02$M_{\odot}$, but the completeness limits are at significantly lower masses. Scaling from literature results in other regions (σ Ori, ONC, Cha-I), we would expect to find 8 – 10 PMOs, but we find none (see Fig 2). This indicates a cutoff in the mass spectrum around the deuterium-burning limit in NGC 1333.

3. ρ Ophiuchus

ρ Oph is one of the closest (d = 125 ± 25 pc, de Geus et al. 1989) regions of active star formation. ρ Oph cluster is not as compact as the first SONYC target NGC 1333, and exhibits extremely high and variable levels of extinction. The main cloud, L1688, is a dense molecular core, with visual extinction up to 50 – 100 mag (Wilking & Lada 1983), hosting an embedded infrared cluster of around 200 stars, inferred to have a median age of 0.3 Myr, and surrounded by multiple clusters of young stars with a median age of 2.1 Myr (Wilking et al. 2005 and references therein).

3.1. Photometry and spectroscopy

For ρ Oph we used the same instrumental setup as for NGC 1333 (Section 2.1), to obtain broad-band images in i', J and K_S, and HK spectroscopy. Completeness limits are placed at i'=24.2, J=20.6, and K_S=17.8. This corresponds to mass limits of 0.004 – 0.1$M_{\odot}$ in the i'-band, and 0.001 – 0.007$M_{\odot}$ in the J-band, for extinction of A_V = 5 –

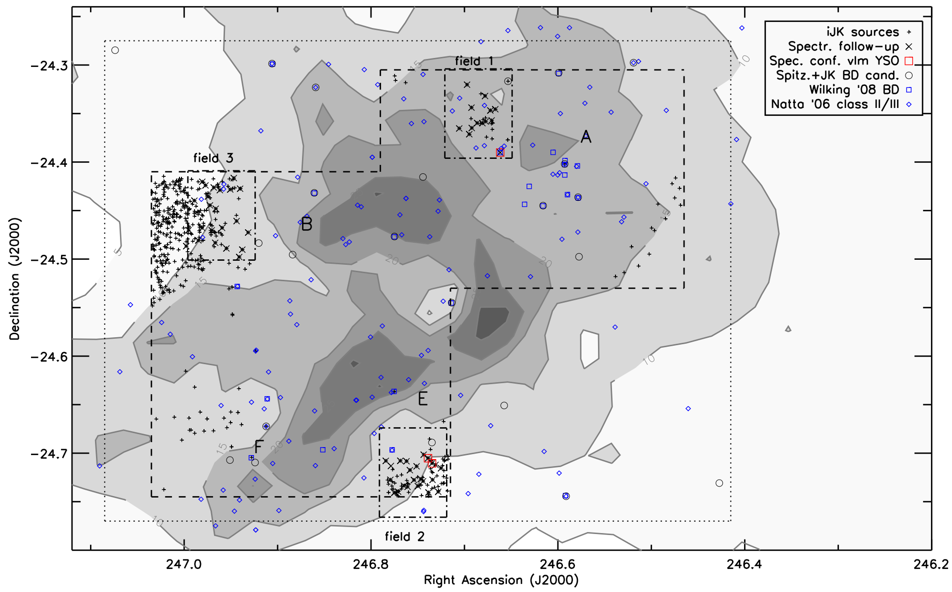

Figure 3. Spatial distribution of sources in ρ Oph. Contours are A_V = 5, 10, 15, 20, 25, 30, as derived from 2MASS by the COMPLETE project. Dotted line: i-band imaging coverage; dashed line: J and K_S-band imaging coverage; dash-dot line: MOIRCS spectroscopy fields. iJK_S catalog sources indicated with +; iJK_S catalog selected BD candidates with follow-up MOIRCS spectroscopy indicated with x; spectroscopically confirmed low mass YSOs are indicated with red large squares. Candidate BDs selected from JK_S + Spitzer photometry indicated with circles. Previously known BDs from Wilking et al. (2008) and class II / III sources from Natta et al. (2006) are indicated with small blue squares and diamonds respectively. Figure from Geers et al. (2010); reproduced by permission of the AAS.

15 (based on the COND03 and DUSTY00 evolutionary tracks). Photometric catalogs were cross-correlated with the existing Spitzer data. The spatial coverage of our $i'+JK_S$ survey is 0.171 deg^2 (see Fig 3).

From the optical and near-infrared photometry, 309 objects were selected as candidate substellar cluster members. 58 of these objects, and 1 additional previously known BD candidate, were targeted for follow-up spectroscopy. Based on multi-object spectroscopy, using the water absorption features in the H-band, 1 of the 58 new candidates was confirmed as a substellar mass object with $T_{\rm eff}$ = 2500 K (see left panel in Fig 4). From MOIRCS, 2MASS, and Spitzer photometry a sample of 27 sources with mid-infrared color excess and near-infrared colors indicative for substellar mass sources with disks are identified. Of these, 11 are previously spectroscopically confirmed brown dwarfs, while 16 are newly identified candidates. Based on present day surveys of the stellar and brown dwarf populations, the ratio of substellar to stellar sources in ρ Oph is derived to have an upper limit of 5 – 7, in line with other nearby young star forming regions. Census of substellar objects in ρ Oph, based on current existing surveys, is likely highly incomplete, due to the variable and high extinction.

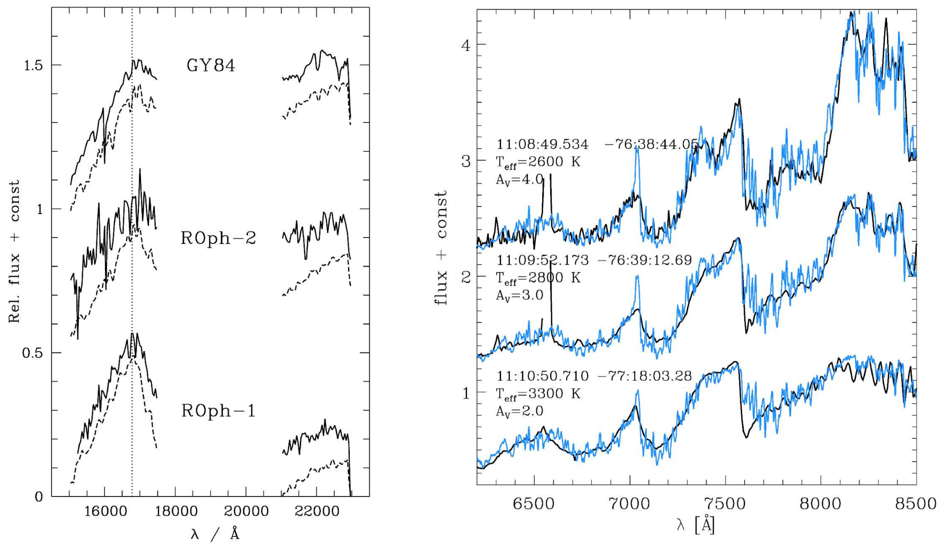

Figure 4. Left panel: MOIRCS spectra (solid) of candidate substellar objects in ρ Oph, with best fit reddened model (dashed) with an T_{eff} of 2500 K, 3100 K, and 3400 K; offsets were applied for clarity. Figure from Geers et al. (2010); reproduced by permission of the AAS. Right panel: Examples of the model fitting for some of the previously known Cha-I candidates. In black are shown the spectra obtained by VIMOS/VLT, with the best-fit models in blue (AMES-Dusty; Allard et al. 2001).

4. Chamaeleon I

At a distance of ~ 160 pc (Whittet et al. 1997), Chamaeleon I (hereafter Cha-I) harbors a rich population of known YSOs (Luhman 2007). Compared to the other two SONYC targets, Cha-I is less compact than NGC1333 and has less extinction than ρ Oph. The spatial coverage of our survey in Cha-I is 0.25 deg^2.

4.1. Photometry and spectroscopy

This study is primarily based on data from the European Southern Observatory, obtained in runs 078.C-0049 and 382.C-0174. The first campaign provided deep optical *iz* imaging (VIMOS/VLT; Le Fèvre et al. 2003), and near-infrared JK_S imaging (SOFI/NTT; Moorwood et al. 1998). In our imaging survey, we reach completeness limits of 23.0 in I, 18.3 in J, and 16.7 in K_S. This corresponds to mass limits of $(0.002-0.01)M_{\odot}$, for $A_V = 0-10$, based on DUSTY00 and COND03 models. From the optical dataset we selected a list of candidate members which were observed using multi-object spectrograph VIMOS/VLT, using the low resolution red grism (5500 – 9000 Å). Additionally, we made use of the archival Spitzer images for our target regions.

4.2. Results

From the optical photometry, 142 objects were selected as candidate substellar cluster members. 60 of these objects have been observed in the spectroscopy campaign, how-

ever, due to the observed limit for spectroscopy at I≈21, only 18 of these candidates have spectra that can be used for classification. In addition, we obtained spectra for more than 200 randomly selected objects in the VIMOS field-of-view. Red portion of M-dwarf spectra is dominated by molecular features (Kirkpatrick et al. 1991, 1995), which allows relatively simple preliminary selection of candidates based on visual inspection. To determine the effective temperature of the remaining candidate objects we performed spectral fitting using the AMES-dusty models (Allard et al. 2001). We identify 13 objects consistent with the spectral type M, of which 11 are previously known M-dwarfs with confirmed membership in the cluster (see right panel in Fig 4). The two newly reported objects have effective temperatures consistent with masses above the substellar limit.

Based on the results of our survey and combined with the numbers of substellar objects from the literature, we estimate that the number of the missing low-mass members down to $\sim 0.008\,M_{\odot}$ for $A_V \leq 5$ in Cha-I is ≤ 7, i.e. $\leq 3\%$ of the total number of members according to the current census. We might, however, still miss objects with lower masses, and objects at higher extinctions.

5. Conclusions

It is clear that the census of BDs and PMOs in most star forming regions is still incomplete. Based on the existing data we can conclude that: (a) there are hints of regional differences in the mass function at the very-low-mass end, and (b) only a combination of different search techniques can provide a robust picture of the substellar population.

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